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# Internet-Based Personal Robot System using Map-Based Localization

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**Abstract**

This paper is about the implementation of an internet-based personal robot system using map-based localization. The idea is to control a personal robot at a remote site by using a simulator provided at a local site. However, if the information of the current absolute position of the robot at its remote site cannot be estimated, the simulator may be useless. The absolute position of the robot can be determined by comparing a reference map of the local site with a map built by a map building technique using sensor information from a laser scanner at the remote site. A user can use three-level control modes - direct control mode, supervisory control mode and job scheduling mode, and monitor the current status of the robot using a graphic user interface (GUI) of the simulator implemented with Java. Experiments with a scenario in a real environment demonstrate the usefulness and the applicability of the internet-based personal robot system.

## 1. Introduction

Telerobotics has made it possible to control a robot at a remote site. This has made it possible to control the motion of the robot at Mars directly [1]. There are many media for teleoperation - internet, telephone line, artificial satellite, etc. Especially, internet is universal and enables users to access any systems on the worldwide network cheaply. In these days, the tendency of electric home appliances is toward home networking. This means that one will be able to control all household electric appliances and monitor the status of one's house at the remote site.

Internet robotics that combines robot with internet made its appearance in the mid 90's, when internet had become universal. It has been observed that many researchers take interest in the area because of the merits of internet. The robot arm control system [2] through a Web browser was designed, and TeleGarden system [3] and Mars Pathfinder [1] were developed. The sensor-based mobile robot system [4] which can be controlled by using a Web browser and the internet-based supervisory architecture [5] were reported. An intelligent telerobot [6] was introduced recently. Most of them have the supervisory control scheme which enables users to issue high level commands. The internet time delay is variable and unpredictable so that the design of a direct control scheme which enables users to control the motion of the robot continuously may not be easy. The direct control scheme [7] on the internet was proposed, but the modeling of the internet time delay was not adequate.

In [8] Kopacek has stated that personal robot is the final application of the household robot which is a kind of service robot. The concept of a personal tele-embodiment was introduced, and the personal robot which enables a user to talk with other persons via internet was implemented in [9]. The robot which can charge its battery by itself was developed in [10]. The research on the interface between human and robots is also important. Hirukawa et al. proposed the standard human interface for internet control in [11], and Backes and Tharp implemented the Web interface for the internet control of the Rocky7 rover in [12]. The remote control interface which enables users to control the Humanoid robot via ISDN was designed in [13], and a collaborative teleoperation, that is, a many-one control architecture via internet was described in [14].

This paper is about the implementation of an internet-based personal robot system with map-based localization. The absolute pose of the robot can be calculated by using the map-based localization technique. Users at the local site can control the robot at the remote site using the developed graphic user interface (GUI) implemented with Java. Only the first user connected to the robot can use the control modes of the GUI, and other users can only monitor the status of the robot. There are three control modes in the developed GUI - direct control mode, supervisory control mode and job scheduling mode. The direct control mode is designed by using the internet control architecture already proposed in [15, 16]. The internet control architecture is insensitive to the internet time delay, and can reduce the path error and the time difference between the real robot at the remote site and the virtual robot of the simulator provided at the local site. In the supervisory control mode, if a user decides a goal position, the robot generates a moving path and moves toward the goal position autonomously. In the job scheduling mode, the user can create a job sequence of the personal robot. The internet-based personal robot is a fully autonomous mobile robot.

This paper is organized as follows. In Section 2, the developed internet-based personal robot system and the modeling of a mobile robot are described. In Section 3, the map-based localization is proposed, which enables the robot to calculate its absolute pose by itself. Section 4 presents the three control modes and the developed GUI. In Section 5, Real experiments with a scenario are provided to show the usefulness and the applicability of the proposed internet-based personal robot system. Concluding remarks follow in Section 6.

## 2. Internet-Based Personal Robot

### 2.1. System description

The internet-based personal robot (IPR), a kind of service robots, can be used for a person's convenient life in a house/office or any indoor environment. It has a personal computer (PC) as a main part, and it can obtain information about environmental changes by using vision cameras, sonar sensors, a laser scanner, etc. Actuators enable the robot to move and to carry out some physical work. It has a wireless LAN system for the internet remote control. A user can control the IPR using the simulator provided at the local site. It has the intelligence to gather the data from the sensors and to process them to decide its action.

The overall system consists of computers at the local sites, internet, wireless LAN system and the IPR. Users can access the IPR located at the remote site via internet using a computer at the local site. The wireless LAN system connects the IPR to the internet.

The developed IPR which is called Mybot is a fully autonomous mobile robot. It can navigate among the obstacles without any supervisor commands. It has its own battery. Its autonomy is for about 5 hours. It can also use the external power via the conventional wired plug. The IPR has a square body of size $45cm \times 52cm \times 75cm$ as shown in Figure 1. The weight is about $75Kg$. It has two drive wheels and two auxiliary off-centered casters. It consists of a personal computer (Pentium III 850MHz), a wireless LAN (Lucent Technologies, 11Mbps), a head with one vision color camera and two DC motors, a 12.1 inch TFT monitor, a speaker, a microphone, sonar sensors (12 pairs), a 12V 100Ah battery (5hr 80Ah), and two brushless DC servo motors (LG Industrial Systems, 200W). Its maximum acceleration rate is $0.52m/sec^2$ and maximum velocity is $209m/sec$. Considering safety, its maximum translational velocity is limited to $50cm/sec$ and the maximum angular velocity is limited to $45\deg/sec$. The CCD camera of the head part can rotate around a vertical and a horizontal axis under the command of the two DC motors. The IPR is connected to the internet through the wireless LAN, and it works as a server. The user can connect to the IPR using a Web browser or a TCP/IP application anywhere.

For the localization purpose, it is equipped with a laser scanner. It gives range information in front of the sensor from $0\deg$ to $180\deg$ at the same time. Its angular resolution is programmable between $0.25\deg$ and $1.0\deg$. The measured data is transmitted by the RS232/RS422 serial communication. In the case of $180\deg$ scanning, it gives 733 bytes. The transmission rate can be raised to 25Hz but the limitation of the serial port of the main computer restricts the rate to 5Hz.


Figure 1: The developed IPR, Mybot

### 2.2. Modeling

The modeling of the IPR is needed for the implementation of the simulator. A two fixed and two auxiliary off-centered orientable wheeled mobile robot with non-slipping and pure rolling is considered. The schematic figure of the developed robot is shown in Figure 2. In the figure, $O_W - X_W - Y_W$ is the global frame and $O_R - X_R - Y_R$ is the robot frame. The translational velocity $v_M$ and the angular velocity $\omega_M$ at

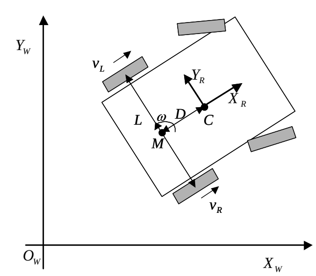


Figure 2: Modeling of Mybot

the center of the wheel base $M$ is obtained from left and right wheel velocities $v_L$, $v_R$ as follows:

$$\begin{bmatrix} v_M \\ \omega_M \end{bmatrix} = \begin{bmatrix} \frac{1}{2} & \frac{1}{2} \\ \frac{1}{L} & -\frac{1}{L} \end{bmatrix} \begin{bmatrix} v_R \\ v_L \end{bmatrix} \tag{1}$$

where $L$ is the wheel base length. $v_R$ and $v_L$ are obtained from the encoders of the two motors.

The robot pose $P_R^W = \left[x_R^W, y_R^W, \theta_R^W\right]^T$ is defined at the center of the robot with respect to the global frame. The kinematic equation of the robot in the global frame is established as follows:

$$\begin{bmatrix} \dot{x}_R^W \\ \dot{y}_R^W \\ \dot{\theta}_R^W \end{bmatrix} = \begin{bmatrix} \cos\theta_R^W & -D\sin\theta_R^W \\ \sin\theta_R^W & D\cos\theta_R^W \\ 0 & 1 \end{bmatrix} \begin{bmatrix} v_M \\ \omega_M \end{bmatrix} \tag{2}$$

where $D$ is the offset distance between $M$ and $C$.

## 3. Map-based Localization

### 3.1. GSP Map

There are three kinds of map representation schemes, a grid map, a feature map and a sensor map which is a collection of recorded sensor data at target places. These representation schemes have their own advantages and disadvantages. If the resolution of the sensor is poor, the grid map shows superior performance. But the grid map has its own inevitable quantization error. The feature map does not induce the quantization error, but it requires a high resolution sensor. In this paper, the feature map is used to localize the robot. It is desired to use simple geometric primitives to reduce computational burden. The most simplest geometric primitive is a line. We propose a generalized symmetric perturbation map (GSP map) using the line segment. A line is usually defined by two line parameters, the orientation $\theta$ and the normal distance to the origin $\alpha$. In this case, the robot pose becomes highly nonlinear to the line parameters. To remedy this problem, three parameters, the position of the center of gravity and the orientation are used to represent the line segment [17].

Suppose that there are $m$ line segments. Then, the GSP map $M$ is defined as follows:

$$\begin{aligned} M &= \{P, L, R, \Xi\} \\ P &= [p_1^T, p_2^T, \cdots, p_m^T]^T \\ L &= [l_1, l_2, \cdots, l_m]^T \\ R &= [R_1^T, R_2^T, \cdots, R_m^T]^T \\ \Xi &= diag(\Xi_1, \Xi_2, \cdots, \Xi_m) \end{aligned}$$

where $p_i = [x_{ci}, y_{ci}, \theta_{ci}]^T$ is the pose of the $i$th line segment, $l_i$ is the length of the $i$th line segment, $R_i$ is the generalized injection matrix of the $i$th line segment and $\Xi$ represents the error covariance of the $i$th line segment which is given as follows:

$$\Xi = \begin{bmatrix} \frac{\Delta_p}{N} & 0 & 0 \\ 0 & \frac{\Delta_p}{N} & 0 \\ 0 & 0 & \frac{\Delta_\theta}{N^3} \end{bmatrix} \quad (3)$$

where $N$ is the number of sensor data which belong to the line segment, $\Delta_p$ and $\Delta_\theta$ are the error covariances of the sensor error. $R_i$ plays an important role to localize the robot.

### 3.2. Localization

The relations of the robot and the line segments in the local map and the global map are shown in Figure 3.

The difference in the corresponding line segments of the local map and the global map are used to correct the error in the robot pose as follows:

$$\begin{aligned} \Delta p_R^W &= \frac{1}{m}\sum_{i=1}^{m} p_{Gi}^W - p_{Li}^W \\ &= \frac{1}{m}\sum_{i=1}^{m} \Delta\tilde{p}_{Mi} \end{aligned} \quad (4)$$

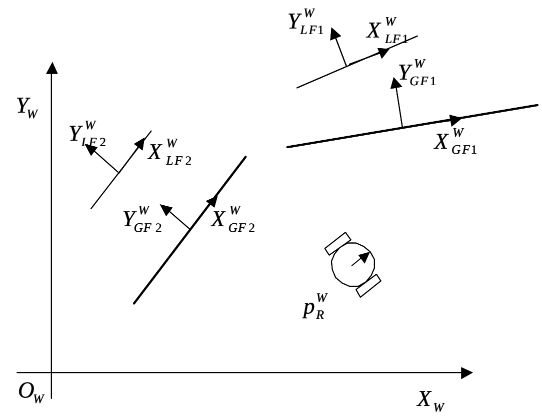


Figure 3: Relations of the robot and line segments

where $p_{Gi}^W$ is the pose of the $i$th line segment in the global map and $p_{Li}^W$ is the corresponding line segment in the local map. $p_{Gi}^W$ and $p_{Li}^W$ are represented in the global frame. If the line segment is finite, (4) is modified as follows:

$$\Delta p_R^W = \sum_{i=1}^{m} w_i \Delta\tilde{p}_{Mi} \quad (5)$$

where $w_i = \tilde{w}_i / \sum_{j=1}^{m} \tilde{w}_j$, $\tilde{w}_i = l_{L_i}/l_{G_i}$, $l_{L_i}$ is the length of the extracted line in the local map and $l_{G_i}$ is the length of the line in the global map.

Suppose that the robot scans a wall which is obscured by an object. The measured line segment in the local map is apparently different from the true value in the global map because of the object. In this case, the estimated robot pose using (5) is incorrect.

Let us define a feature frame of which $X_F$ axis is aligned to the line. To consider the line symmetry, let us convert $\Delta\tilde{p}_{Mi}$ into the feature frame. The difference along $X_F$ axis should not be considered and differences in $Y_F$ coordinate and $\theta_f$ direction should only be considered. The following error can be obtained in the feature frame:

$$\begin{bmatrix} \Delta x_{fi} \\ \Delta y_{fi} \\ \Delta\theta_{fi} \end{bmatrix} = \begin{bmatrix} 0 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} \cos\theta_i & -\sin\theta_i & 0 \\ \sin\theta_i & \cos\theta_i & 0 \\ 0 & 0 & 1 \end{bmatrix} \Delta\tilde{p}_{Mi} \quad (6)$$

As the robot pose is represented in the global frame, another rotational matrix is needed. Thus, we can obtain the following relations between the error of the robot pose and the feature difference:

$$\begin{aligned} \Delta p_{Mi} &= \begin{bmatrix} \sin^2\theta_i & -\sin\theta_i\cos\theta_i & 0 \\ -\sin\theta_i\cos\theta_i & \cos^2\theta_i & 0 \\ 0 & 0 & 1 \end{bmatrix} \Delta\tilde{p}_{Mi} \\ &= R_i \Delta\tilde{p}_{Mi} \end{aligned} \quad (7)$$

where $R_i$ is called a generalized injection matrix. The error of the robot pose is estimated as follows:

$$\Delta p_R^W = \sum_{i=1}^{m} w_i \Delta p_{Mi} \quad (8)$$

And the corrected robot pose is calculated iteratively as follows:

$$p_R^W(k+1) = p_R^W(k) + \Delta p_R^W(k) \quad (9)$$

## 4. User Interface

### 4.1. Control Methods

A user can control the IPR at the remote site via internet using the developed GUI provided at the local site. The user regards the status of the virtual IPR at the local site as that of the real IPR at the remote site. Since the user cannot recognize the environment of the remote site, it is expected that the real IPR moves as the virtual IPR does.

There are three control modes in the GUI implemented with Java - direct control mode, supervisory control mode and job scheduling mode. The user can control the motion of the robot directly using the direct control mode. In the supervisory control mode, if the user decides a goal position, the robot generates a moving path and moves toward the goal position autonomously. In the job scheduling mode, the user can create a job sequence for the personal robot.

In the direct control mode, because of time delay we have to compensate for the path error and the time difference between the real robot and the virtual robot, which increase as time goes on. In this paper, the internet control architecture proposed in [15] is considered. The architecture is insensitive to the internet time delay, and can reduce the path error and the time difference between the real robot at the remote site and the virtual robot of the simulator provided at the local site. The performance of the architecture was proved in [15], and the experimental results using the developed IPR were described in [16]. The internet control architecture used in the direct control mode is as shown in Figure 4.

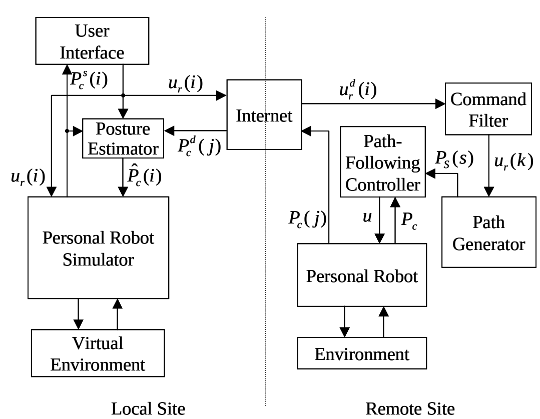


Figure 4: Internet control architecture

In the supervisory control mode, the goal position and the final heading angle on the map are the control commands. After the goal position is determined, the shortest moving path is generated by using the "via" points which were already given in the map. The via points can be considered as all the points in the path through which the robot passes.

In the job scheduling mode, one job sequence can be determined by using the several jobs given in the menu of the GUI. In the GUI of Mybot, four jobs are given, such as MOVE, VOICE, MESSAGE and WAIT. MOVE means 'move toward the goal position,' VOICE 'speak the words provided by the user,' MESSAGE 'show the messages written by the user to the monitor,' and WAIT 'wait for the specified time.'

### 4.2. GUI

The developed GUI was implemented with Java 1.3. So as to use the GUI, the user only needs to connect the personal robot using a Web browser. The Web browser connected to the robot will load the Java class file of the GUI automatically. The GUI loaded in the Web browser is shown in Figure 5. The

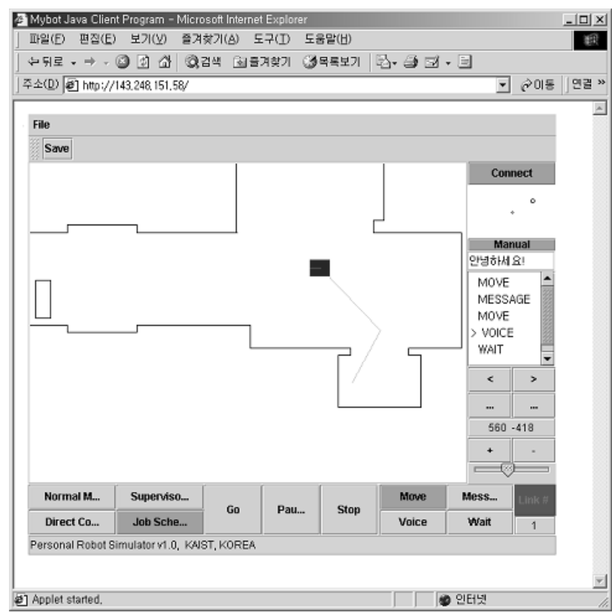


Figure 5: GUI implemented with Java

GUI is linked with the robot using TCP/IP. Only the first user connected to the robot can use the control modes of the GUI, and other users can only monitor the status of the robot. In the center of the GUI, the map and the status of the robot are displayed. In the bottom of the GUI, there are four buttons for the selection of the control modes, and several buttons for generating the commands. On the right side of the GUI, the controls for the motion of the CCD camera mounted on the top of the robot and for checking the job sequence exists. The order and the status of connection can be verified using the right bottom of the GUI.

When the user connects to the robot using a Web browser, the image of the CCD camera and the sound as well as the GUI pop up. The maximum frame rate of the image is 5 frames per second, and the RTP protocol is used for the transmission of the image and the sound.

## 5. Experiment

Experiment was performed with the developed IPR in the real internet environment. In this experiment, we provided a scenario with a job sequence. The point A on the map shown

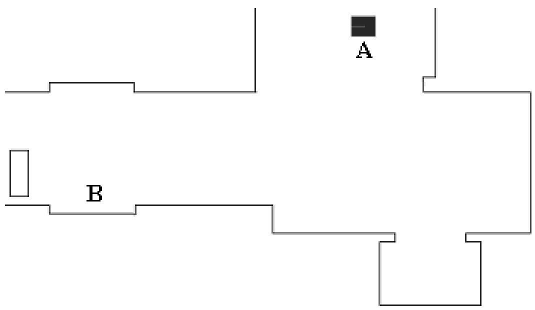


Figure 6: Experiment with a scenario

in Figure 6 was the initial position of the robot, and the point B was the goal position.

The scenario for the experiment is as follows: Mybot moves from A toward B in front of the door, and says "Hello!" After saying that, Mybot shows a message, "Please put the book on my top side!" After someone puts it with the enter key pressed, Mybot moves toward the start point A.

The job sequence ordered to the robot is as follows:

- MOVE (B)
- VOICE (Hello)
- MESSAGE (Please put the book on my top side!)
- WAIT(until the enter key is pressed)
- MOVE (A)

The expermental result with this scenario was a success. The robot received the book at the point B, and brought it to the person at point A. When someone passed near the robot, it avoided the person without any supervisor commands. The experiment demonstrated the applicability of the IPR system.

## 6. Conclusions

This paper presented the implementation of the internet-based personal robot system using map-based localization. The developed IPR was a fully autonomous mobile robot. The absolute pose of the robot could be calculated by using the map-based localization technique. A user could control the personal robot at the remote site using the developed GUI loaded in a Web browser, where three control modes - direct control mode, supervisory control mode and job scheduling mode were provided. The GUI implemented with Java enabled the user to control and monitor the robot. The image of the CCD camera mounted on the top of the robot and the sound were also transmitted to the user. The experimental result with a scenario demonstrated the usefulness and the applicability of the IPR system.

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